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Seismic imaging at a mineral-deposit scale using high-frequency surface waves (0.5–24 Hz) in ambient noise wavefield

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Summary

Ambient noise, surface-wave tomography (ANSWT) is now a routine technique for imaging crustal and upper mantle structure at a regional scale. Its cost efficiency and environmental friendliness also make ANSWT an attractive method for mineral exploration. However, the application of the technique in mineral exploration requires the retrieval of wide-band, high-frequency surface waves from seismic noise, so as to obtain high-resolution images of shallow structures. We present a new workflow optimized to extend the bandwidth of high-frequency surface waves retrieved. It comprises short time-window stacking, cross-coherence and an improved phase velocity measurement method. We tested the workflow on data from a large-N array over a Cu-PGE deposit in Ontario, Canada, and successfully measured phase velocities for numerous inter-station pairs in a broad frequency ranges from 0.55 Hz to 23.8 Hz. Analysis of the phase velocity maps reveals a west-dipping high-velocity anomaly that matches the west-dipping, multi-staged gabbro intrusions associated with the deposit.

Introduction

Ambient noise surface wave tomography (ANSWT) has evolved since its first applications (Shapiro, 2005) as a routine technique for imaging crustal and upper mantle structure. The cost efficiency and environmental friendliness of the approach also make ANSWT an attractive method for mineral exploration. However, high-resolution imaging of shallow structure at depths relevant to mineral exploration requires measurements of surface-wave speeds at frequencies much higher than in the conventional, crustal-scale applications.

Frequency range of surface waves recovered from the ambient noise depends on the bandwidth of noise sources and appropriate normalization of seismic records (to satisfy the condition of noise interferometry theory). Dispersion measurement method effective at high frequencies is also required. Here, we present an optimized workflow for the retrieval of reliable, wide-band, surface-wave phase velocity measurements from the ambient noise. We use an application to a large-N array over a Cu-PGE deposit in Ontario, Canada, to demonstrate and validate the workflow developed.

Method

Although the details vary, most of the ANSWT studies comprise the following key steps: splitting continuous records into segments, bandpass filtering, temporal normalization, spectral whitening, cross-correlation and stacking (Bensen et al., 2007). Our new correlation method, aiming to broaden the bandwidth of the surface waves retrieved, removes the bandpass filter, replaces temporal normalization with short segment stacking and replaces spectral whitening and cross-correlation with cross-coherence. Hence, the key steps are now the cutting of continuous records into *short* segments, cross-coherence and stacking.

Phase velocity measurements are performed using frequency-time representation of the surface waves. Traveltime of surface waves at different frequencies are measured and converted to phase velocity. Multiple waveform ridges in surface waves are combined so as to extend the bandwidth, especially for the high frequency limit. Using a dense array, measurements from station pairs with different interstation distances but sampling roughly the same location can also be averaged, in order to extend the bandwidth further.

Examples

Situated at the east margin of Coldwell Alkaline Complex in Ontario, Canada, the Marathon Cu-PGE deposit was formed following magma flow upwards along the feeder channels between gabbro intrusions and an Archean footwall (Good et al., 2015). The EU Horizon 2020 project PACIFIC (Passive seismic techniques for environmentally friendly and cost efficient mineral exploration) chose the Marathon deposit as one of the two sites used to develop and validate exploration techniques.

A large-N array was deployed over the deposit for 1 month in 2018 in order to obtain ambient noise data. The array comprised 1020 sensors and comprised a rectangular array with 150 m spacing and an overlapping “fat line” array with 50 m spacing. We computed the noise cross-correlation functions (NCFs) using the proposed workflow. Experiments on the convergence of NCFs with the time span of the recordings used showed that 0.5 – 3 hours are sufficient to obtain a reliable dispersion curve in most cases. We selected the first hour of the day 2018-

10-01 to demonstrate the proposed workflow. The time windows used were 1 min long, with a 50% overlap with the nearest neighbours.

In total, 73724 NCFs were computed. Clear surface wave signals can be observed in the profile of NCFs, with a relatively high apparent velocity of 3 km/s. The high velocity is consistent with the mafic/ultramafic igneous rock outcrops in the Marathon area. Phase velocity was measured using the multiple filter technique. We developed an amplitude-guided ridge tracking method that trace along the appropriate ridges in surface waves to get a wider band measurement.

Phase-velocity maps were obtained using a moving-average approach that assembled station pairs with middle points close to a centre point and assigned the resulting average dispersion curve to the point. Phase velocities at 11×7 points were evaluated to form phase-velocity maps (Fig. 1). The multi-staged gabbro intrusions are outlined by black lines in the maps and are collocated with high-phase-velocity anomaly. Considering the inverse relationship between the depth sensitivity and frequency of surface waves, the westward displacement of the high velocity anomaly with decreasing frequency indicates a west-dipping structure of a high-velocity material, most likely the gabbro intrusions. The upper and lower boundaries of the anomaly correspond to the contact with syenite above and the Archean metavolcanics rocks below, respectively, according to the geological record.

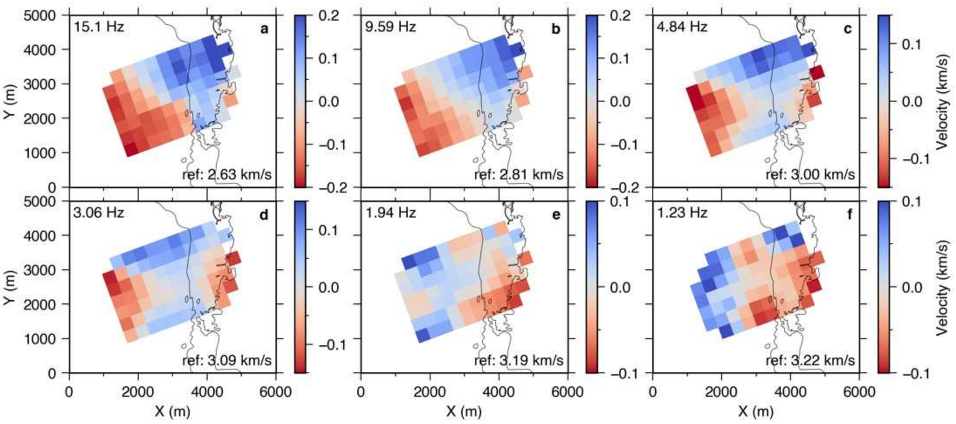

Figure 1 *Phase-velocity maps at the Marathon site. Higher frequency maps correspond to shallower structure and lower frequency maps correspond to deeper structure. (a) Map at a frequency of 15.1 Hz. The blue-red mosaic shows the phase-velocity anomaly with respect to the reference velocity labelled at the lower right corner of each panel. Black lines outline the multi-staged gabbro intrusions. (b) Same as (a) but at 9.59 Hz. (c) 4.84 Hz. (d) 3.06 Hz. (e) 1.94 Hz. (f) 1.23 Hz.*

Conclusions

A new workflow for ambient-noise, surface-wave tomography is proposed in order to extend the bandwidth of the surface waves retrieved from the ambient seismic noise. An application to the Marathon site demonstrates its ability to retrieve wide-band, high-frequency measurements (0.55- 23.8 Hz) and to image deposit-related structures.

Acknowledgements

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